Modulated ECH Experiments in Off-axis Heated RTP plasmas

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In the RTP tokamak (R=0.72 m, a=0.16 m, B_T<2.4 T, I_p<150 kA) the plasma response to changes in the resonance position (ρ_{dep}) of the Electron Cyclotron Heating (350 kW at 110 GHZ, X-mode, 2nd harm injected from LFS) has been investigated under conditions where the ECH power is much larger than the Ohmic power [1]. Strong off-axis heating results in pressure, current and safety factor (q) profiles that can be very different from the "canonical " Ohmic profiles. Furthermore the changes occur discontinuously as ρ_{dep} is moved away from the magnetic axis. This is manifested in the behaviour of the central electron temperature (T_e) as a function of ρ_{dep} (Fig.1), which shows plateaux separated by suddens jumps. The occurrence of a jump is well correlated with the loss of a low order rational q surface (Fig.2). This has been interpreted as evidence for a special role of rational q surfaces in electron energy confinement: the existence of transport barriers (i.e. thin layers of low thermal diffusivity) in the proximity of rational q surfaces can account for the experimental evidence of Fig.1 and the measured steady state T_e profiles for the five plateaux A-B-C-D-E [2].
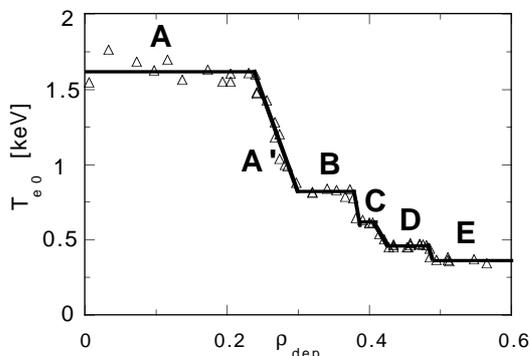

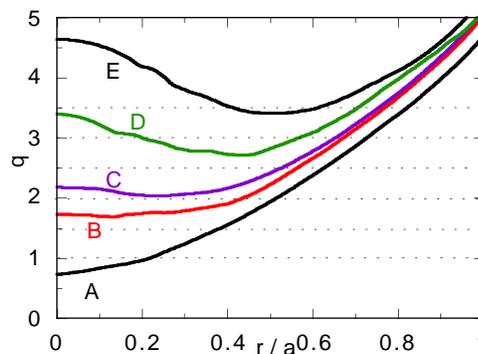*Fig.1: T_{e0} vs. ρ_{dep} in a B_T scan experiment.*

Fig.2: q profiles for 5 discharges representative of the 5 plateaux of Fig.1.

In this paper, further evidence is presented on the thermal transport properties of ECH dominated plasmas. The evidence comes from modulated ECH (MECH) and complements the steady-state observations summarized in Fig.1. MECH with high duty-cycle (f=312Hz, d_c=0.87) was applied to plasmas in the 3 plateaux A-B-C of Fig.1 and to the sub-plateau A' identified in [1] as intermediate between A and B (in A' q=1 has been lost, but q=3/2 is still present). High duty cycle is required in order to have a large time-averaged ECH power. The T_e profiles measured during the ON phase of MECH are shown in Fig.3, as measured by Thomson scattering and ECE diagnostics. The Thomson scattering diagnostic had a superior spatial resolution but missed the plasma axis in these experiments due to the Shafranov shift of

about 2 cm. Hence the need to complement it with ECE observations which, however, do not resolve fine details of the T_e profile.

An important observation can be made by noting the ρ_{dep} positions in Fig.3: the peak T_e values occur at positions shifted towards the centre with respect to ρ_{dep}. This is most evident for the A plateau (where T_e is peaked on-axis for a relatively large value of ρ_{dep}=0.24) but is clear also for the other plateaux, some of which feature hollow T_e profiles. Of course this observation is at odds with diffusive transport models - with or without barriers. When observations somewhat similar to these were made on DIII-D [3], the presence of a heat pinch was postulated in order to explain the permanence of peaked T_e profiles in the presence of off-axis ECH. The DIII-D interpretation can be reassessed on the basis of the present RTP results that extend the DIII-D ones in two ways: i) a wider range of ρ_{dep} has been explored, extending the observations to hollow T_e equilibria; ii) heat wave propagation measurements have been made. The latter proved quite useful for checking the a-priori determination of ρ_{dep} and, especially, for searching for convective-like components in the heat flux.
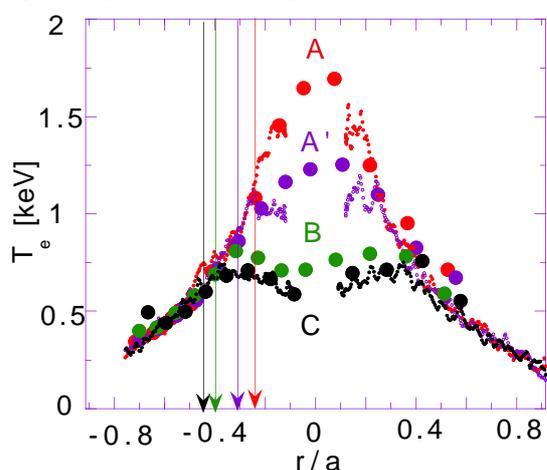

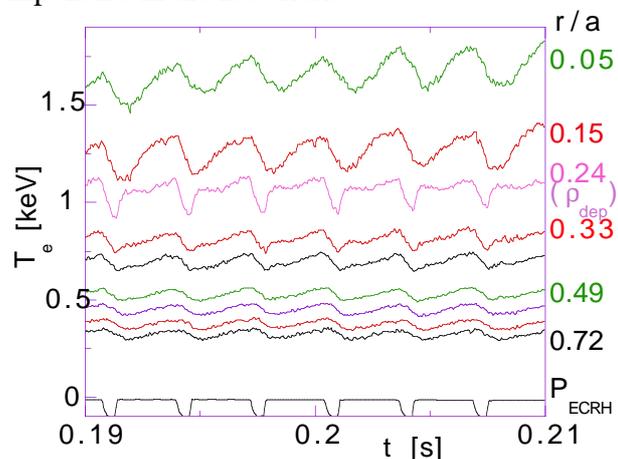*Fig.3: ECE and TS T_e profiles in MECH discharges for plateaux A-A'-B-C.*

Fig.4: time evolution of ECE T_e for the MECH discharge in plateau A shown in Fig.2.

Fig.4 shows ECE time traces at several radial positions for the plateau A discharge of Fig.3. The channel closest to ρ_{dep} (marked) features the fastest response to MECH as expected. Surprising is the large modulation amplitude of the channels inside ρ_{dep}. This is analysed in more detail by Fourier analysis. In Fig.5 Fourier amplitudes (A) and phases (φ) for the first 3 MECH harmonics are shown for the discharges in plateaux A, A' and C of Fig.3. The following observations can be made:

1) φ is minimum at ρ_{dep} at all harmonics;

2) A at 1st harmonic is largest at positions inside ρ_{dep} - a remarkable non-diffusive feature;

3) the A profile at higher harmonics recovers a diffusive-like shape with the maximum coinciding with the φ minimum and with ρ_{dep};

4) both A and φ profiles are strongly asymmetric around ρ_{dep}: the spatial derivatives A'/A and φ' are larger inside than outside ρ_{dep}.

Points 1) and 3) provide an empirical evidence confirming the theoretical ρ_{dep} value. On the other hand, the presence of a non-diffusive process is indicated by the inward shift (relative to

ρ_{dep}) of the T_e and 1st harmonic A peaks in Figs.3 and 5. The fact that this shift affects only the first harmonic amplitudes but not the phases and that it tends to disappear at higher harmonics suggests that some form of inward convection be at work in a plasma layer just inside ρ_{dep} [4].
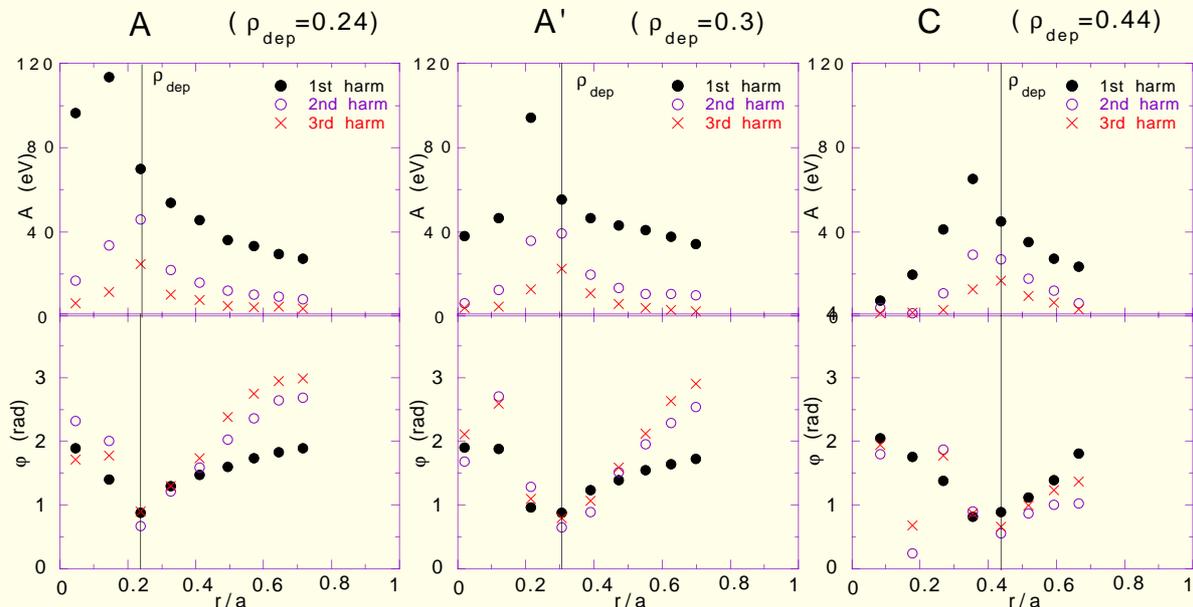

Fig.5: A, φ profiles at 3 harmonics for the MECH discharges A-A'-C of Fig.2 (f=312 Hz, dc=0.875). The location of ρ_{dep} is marked by vertical lines.

A preliminary 1-D full transport simulation has been performed using the ASTRA code [5] to estimate the amount of inward convective transport required to match the observations. For simplicity a smooth diffusivity profile has been used in the standard heat transport equation; a heat pinch term in the heat flux ($q_{conv}=nUT_e$) has been added where U has a Gaussian profile, see Fig.6. The resulting simulated profiles for T_e, A, φ are shown in Fig.7. For comparison a simulation with a pure diffusive model is shown. From these simulations we can conclude that:
- a heat pinch term localized in the region $\rho<\rho_{dep}$ <u>is required</u> to reproduce the set of observations described in points 1), 2), 3); a U profile with peak value of -60 m/s and FWHM of about 1.5 cm is found to be the best choice to fit the experimental data (see Fig.6).
- the presence of a heat pinch does not explain the asymmetry between the two sides of ρ_{dep}, which is observed both on amplitudes and on phases (point 4)). This requires a χ_e profile strongly increasing with radius, such as shown in Fig.6. In particular low values of χ_e are required in the region $\rho<\rho_{dep}$ to reproduce the high values of φ' and A'/A at high harmonics, while high values of χ_e are required in the region $\rho>\rho_{dep}$ to reproduce the slow fall-off of the perturbation. We note that due to the high χ_e value the data at 1st harmonic in the external region ($\rho>0.4$) are sensitive to the boundary condition [4]. Therefore they are not useful for transport analysis in this region. We also remark that a similar asymmetry is observed in ASDEX Upgrade, and described in terms of an asymmetry in the $\chi_e^{pert}/\chi_e^{PB}$ ratio [6].
- the comparison between data and simulation reveals further features in the data that are not easy to reconcile with the simple model used. In particular, the sharp drop of A inside ρ_{dep} at

high harmonics would require an even lower diffusivity, which would be on the other hand difficult to reconcile with the measured steady-state T_e profile. Moreover, a $\chi_e^{pert}/\chi_e^{PB} > 1$ value outside ρ_{dep} would be required, such as previously observed on RTP [7]. This calls for a refinement with respect to the present modelling.
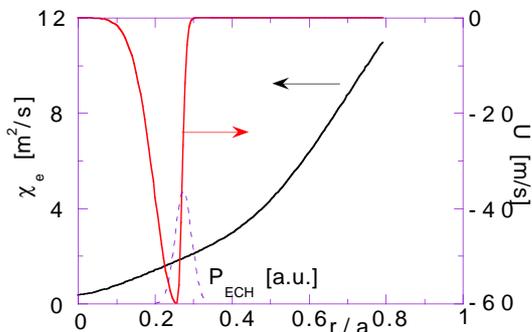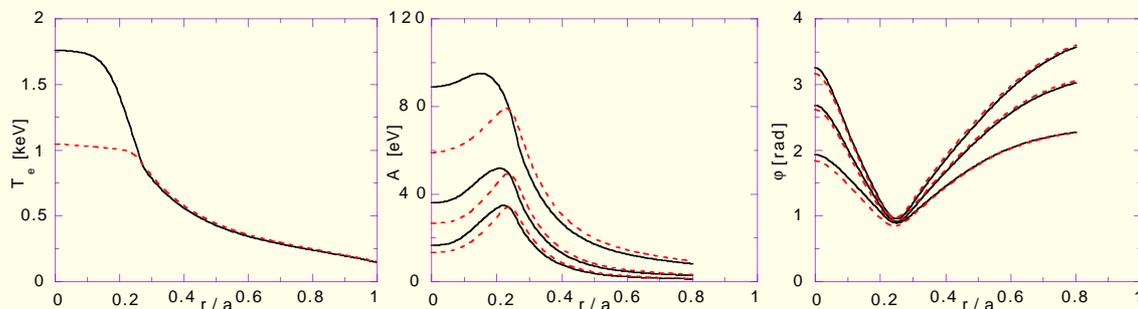

Fig.6 : χ_e and U profiles used in the simulation of Fig.7. The ECH power deposition profile is also shown.

Fig.7 (below): simulated T_e, A, φ at 3 harmonics for the discharge in plateau A using the model illustrated in Fig. 6 (full lines). For comparison, a simulation with the same χ_e but U=0 is also plotted (dashed lines).

The observation of non-diffusive transport in ECH-dominated RTP plasmas can have interesting consequences. These are the same plasmas that provide evidence for the existence of transport barriers in the ρ_{dep} scan experiment of Fig.1. The MECH observations do not provide a clear evidence of diffusive barriers but they do not disprove their existence either. Certainly the details of the model of [2] will have to be revised in light of the new findings - especially the core χ_e value. An interesting hypothesis that can be formulated here is that the barriers may be convective rather than diffusive. What remains unchanged is the evidence of a sudden loss of energy confinement in the plasma core when a low order rational q surface is lost, see Figs.1-3. In this sense, the concept of transport barriers remains valid even if more sophisticated models may have to be invoked to account for all the experimental evidence gathered on RTP. 3-D (e.g., m=1) convective cells, such as described in [8] may represent an element in this model. However what needs to be investigated is i) how they can effectively improve confinement and ii) what is the response to modulated ECH of a plasma with 3-D convective cells.

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